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Soil and sugar maple response to 8 years of NH_4NO_3 additions in a base-poor northern hardwood forest

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ABSTRACT

Ammonium nitrate was added annually at 3- and 10-fold the ambient wet atmospheric deposition rate (8.5 kg ha^{-1} year^{-1}) during 8 years in a base-poor northern hardwood forest of Québec, Canada. Soil chemistry and foliar chemistry, crown dieback and basal area growth of sugar maple (*Acer saccharum* Marsh.) were measured after 8 years of treatments. Despite repeated N additions, N concentrations in all soil layers remained similar between treatments. However, the treatments significantly reduced exchangeable Ca, Mg, Mn and K compared to the untreated plots, at least for one of the top organic soil layers. The most significant and substantial differences were observed for Ca between the control and the high N treatment, with the L and the H layers showing decreases of 29% and 72%, respectively. Foliar Ca and Mn concentrations decreased with increasing levels of N addition, while foliar N increased. Foliar Ca in the high N treatment decreased by 79% compared to the control and reached 0.24%, the lowest foliar Ca concentration ever reported for sugar maple. No significant treatment effects were observed for dieback rate or basal area growth, although mean dieback rate of sugar maple in the high N treatment was 43% higher than in the control. Our results show that increased N deposition, even at relatively low rates, can strongly affect Ca nutrition of sugar maple at sites with low base cation saturation. This raises concerns about the sustainability of sugar maple in acidic, base-poor forest soils.

1. Introduction

Since the early 1980s, decreasing vitality of sugar maple (*Acer saccharum* Marsh.) has been a major concern in poorly buffered soils of northeastern North America (Duchesne et al., 2002; Horsley et al., 2002; Gavin et al., 2008; Long et al., 2009; Watmough, 2010; Moore et al., 2012). Sugar maple is known to be very sensitive to soil acidity (Thornton et al., 1986; Ouimet et al., 1996). In survey plots in Vermont, Wilmot et al. (1995) observed a strong correlation between soil pH and sugar maple dieback. In addition, many studies on sugar maple dieback have suggested that base cation deficiency, and particularly Ca deficiency, was a cause of tree growth reduction and decline (Huggett et al., 2007; Long et al., 2009; Watmough, 2010). Moreover, the positive growth and vigor response of sugar maple to liming or Ca addition in base-poor northern hardwood stands has demonstrated that Ca deficiencies are involved in the decline of sugar maple at many sites (Wilmot et al., 1996; Huggett et al., 2007; Long et al., 2011; Moore et al., 2012).

Many studies have suggested that acid deposition has accelerated the loss of available Ca from soils with a low acid-buffering capacity in northern hardwood stands (Houle et al., 1997; Likens et al., 1996; McLaughlin, 1998; Bailey et al., 2005; Long et al., 2009). Duchesne et al. (2002) showed that the appearance of the sugar maple decline phenomenon and the associated growth reduction can be related, at least in part, to soil acidification and acid deposition levels in Québec. SO_4 and NO_3 are the major anionic components of acid deposition. In recent decades, S emissions and deposition have decreased in northeastern North America (Driscoll et al., 2001; Houle et al., 2004), due to a series of regulations designed to reduce S emissions from power plants and vehicles (NADP, 1998). Similar regulations have also targeted N deposition (US EPA, 2010) and have resulted in significant reductions in NO_x emissions and deposition, both in the United States (US EPA, 2010; Pinder et al., 2011; Templer et al., 2012) and in Canada (Geddes et al., 2009). The same decreasing trend in NO_x deposition has been observed in some areas of Québec (L. Duchesne, unpublished data), including the study area. Unlike NO_x emissions, NH_3 emissions are unlikely to decline, and an increasing trend has been reported in the United States (Templer et al., 2012). Thus overall, studies show that global atmospheric N deposition has doubled in the last one hundred years and is projected to more than double in the next century, mainly due to fossil fuel combustion and growing demand for N by agriculture and industry (Galloway et al., 2004, 2008).

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In the last decades, a growing number of northern hardwood forests have showed signs of N saturation, both in the United States (Gilliam et al., 1996; Mitchell et al., 1996; Peterjohn et al., 1996; Adams et al., 1997; Lovett et al., 2000; Aber et al., 2003) and Canada (Foster et al., 1989; Moayeri et al., 2001). One of the major symptoms of N saturation is an elevated loss of NO_3 to ground and surface waters (Fenn et al., 1998). Other symptoms are increasing N concentrations and higher N:nutrient ratios in foliage. Increased NO_3 leaching may lead to higher leaching losses of base cations (Fenn et al., 1998), and to increased Al mobility and soil acidification (Johnson et al., 1991). These changes may lead to nutritional imbalances (Schulze, 1989), including foliar Ca depletion (Schaberg et al., 2001), decreases in tree growth and productivity (Aber et al., 1995; McNulty et al., 1996) and eventually, forest dieback (e.g., Aber et al., 1989; Schulze, 1989; Skeffington and Wilson, 1988). Aber et al. (2003) reviewed existing datasets and concluded that N deposition was altering N status in forests of the northeastern United States.

Over the last decades, several chronic N addition experiments have been performed to simulate high atmospheric N deposition in sugar maple-dominated stands of northeastern North America (Ellsworth, 1999; Elvir et al., 2003, 2006; Mitchell et al., 2003; Pregitzer et al., 2004; Zak et al., 2004; Moore and Houle, 2009). These studies showed that higher N deposition could eventually alter stand dynamics by affecting sugar maple seedling survival and Ca nutrition. However, only three chronic N addition trials are still being monitored in sugar maple stands: the first at the Bear Brook Watershed in Maine (USA; 1989–present; Elvir et al., 2010), the second in Michigan (USA; 1994–present; Patterson et al., 2012) and the third at the Lake Clair Watershed (LCW) in Québec (Canada; 2001–present; Moore and Houle, 2009). Short-term results of the latter study showed that chronic N additions decreased foliar Ca concentration of sugar maple, but did not affect tree growth and health. It was hypothesized that the lack of initial response was due to the short monitoring period.

The objective of this study is to determine the medium-term effects of N additions (three- and ten-fold current atmospheric N deposition levels), as NH_4NO_3, on soil chemistry and sugar maple foliar status, crown dieback and growth, for the sugar maple stand of the LCW growing on poorly buffered soils with low Ca availability (Houle et al., 1997; Duchesne et al., 2002). We hypothesized that 1) 8 years of chronic N additions would result in a lower availability of exchangeable Ca in soils of treated plots, and 2) the decreased availability of Ca would negatively affect Ca foliar chemistry, crown vitality and growth of sugar maple.

2. Materials and methods

2.1. Study site

The Lake Clair Watershed (LCW, 226 ha including a 36 ha lake, 46°57′N, 71°40′W, 270–390 m above sea level) is located approximately 50 km northwest of Québec City (Québec, Canada). The mean slope is approximately 10%. Mean annual temperature is 3.4 °C and annual precipitation is 1300 mm. The forest in this area is uneven-aged and composed of sugar maple in association with yellow birch (*Betula alleghaniensis* Britt.) and American beech (*Fagus grandifolia* Ehrh.). These tree species represent approximately 75%, 16% and 8% of the basal area of the study site, respectively. Soils are classified as Orthic Ferro-Humic Podzol (Canada Soil Survey Committee, 1998), or Typic Haplorthod (Soil Survey Staff, 1998). The humus is a mor-moder type and the surface deposit is a very acid and stony glacial till derived from granitic gneiss bedrock.

2.2. N addition trial

For the fertilization trial, a representative area of the whole watershed in terms of tree ages, stand density and composition was selected at the border of the LCW. In this area, 12 experimental units (15 × 15 m) were chosen, but only 9 were used for this experiment. Experimental units had to be at least 10 m apart from each other, but were often more than 15 m apart. Treatments were randomly assigned to three replicate blocks. NH_4NO_3 was diluted in 20 L of deionized water. Nitrogen application rates were 3- and 10-fold the annual precipitation of N at this site (Low $N = 26$, High $N = 85$ kg N ha^{-1} year^{-1}). The additions were done in four passes with a Solo® backpack sprayer. From 2001 to 2008, fertilizer was applied monthly, 5 times a year, from June to October. Before treatment, sugar maple trees on the 9 experimental plots had a mean diameter at breast height of 26.1 ± 8.3 cm; mean basal area growth was only 6.0 ± 1.1 cm^2 year^{-1}, presumably because of poor soil conditions (Houle et al., 1997; Duchesne et al., 2002).

2.3. Field sampling

2.3.1. Soil chemistry

In each of the 9 experimental plots, 3 soil profiles were sampled in 2008 and pooled according to soil horizons. The L, F and H layers were quantitatively sampled on a 177 cm^2 surface up to the top of the mineral horizon. Since the Ae horizon was very thin and discontinuous at this site, it was not sampled. The first 20 cm of the B horizon (top B horizon) and the soil at depths of 20–40 cm (lower B horizon) were then sampled with an Edelman type soil auger.

2.3.2. Vegetation

In each experimental unit, five dominant or co-dominant sugar maple trees were selected and numbered in October 2000, for a total of 45 trees. To avoid border effects, the trees closest to the center of each plot were selected. Their crown did not exceed the plot borders. In August 2008, approximately 40 leaves from each tree were collected at mid-crown with a telescopic pole pruner, on two opposite branches. This time of the year, i.e. preceding foliar coloration, corresponds to stable foliar concentrations in sugar maple (Duchesne, 1998).

After the 2008 growth season, 2 increment cores were taken to measure radial growth on the same trees used for foliar sampling. Annual rings were measured using WinDendro software (version 6.1D, Régent Instruments Inc., 1998) and validated with signature rings. Ring values were converted to basal area increment (BAI) using the following equation:

$$\mathrm{BAI}_t\ (\mathrm{cm}^2) = \pi(R_t^2 - R_{t-1}^2)$$

where R is the tree radius (cm) and t is the year of tree ring formation.

In the summers of 2005 and 2008, on the same day as foliage sampling, the same two experienced observers conducted a careful visual inspection to estimate the percentage of missing crown foliage (by 5% class intervals) and evaluate crown dieback. This technique was also used in other sugar maple studies (Moore et al., 2012).

2.4. Chemical analyses

Soil samples were air-dried, ground, and sieved to 2 mm. The soil samples were treated with an unbuffered NH_4Cl solution (1 M, 12 h, mass: volume ratio of 1:10). Soil pH was measured directly in the extract with a pH probe, and exchangeable cations (Al, Ca, Mg, Mn, K) were measured using atomic emission spectrometry (ICP, Perkin Elmer Plasma Model 40). Total N was

determined by titration following Kjeldahl digestion (Kjeltec Tecator 1030).

Foliar tissues were dried at 65 °C and ground to 250 μm. Nitrogen content was determined following Kjeldahl digestion (Kjeltec Tecator 1030). P, K, Ca, Mg and Mn contents were measured by atomic emission spectrometry following the digestion of 500 mg of foliage with H_2SO_4.

2.5. Statistical analyses

ANOVAs were performed on soil (on an air-dry basis) and foliage variables, and on dieback rate using treatment as a fixed factor. For basal area growth, the pre-treatment measures of 1999–2000 were used as covariables. Polynomial contrasts were built to assess the effect of N additions. All analyses were performed using the SAS Mixed procedure (SAS Software Inc., 2000).

3. Results

3.1. Effects of N treatments on soil chemistry

Soil pH was not significantly different between treatments, with global means of 3.49, 3.00, 3.23, 3.97 and 4.11 for the L, F, H and top and low B horizons, respectively. Despite 8 years of N additions, N concentrations remained similar in all soil layers between treatments. No significant treatment differences were observed for the mass of the organic layers (L, F and H) or the N mass comprised within these layers (data not shown). However, the treatments had a significant effect on exchangeable Ca in the L, F and H layers, Ca concentrations being generally lower in treated plots (Fig. 1). Most significant effects were observed between the control and the high N treatment. For instance, in the high N treatment, Ca was reduced by 29% in the L layer and by 72% in the H layer, as compared to the control. In the F layer, Ca was also lower in the high N treatment by 47% as compared to the control, but this difference was not significant due to a higher variability between replicates. Similar results were obtained for Mg, with significant decreases in the high N treatment, but this time for the L and the F layers. Significant decreases were also observed for exchangeable Mn and K, in the F layer.

3.2. Effects of N treatments on sugar maple trees

After 8 years of treatments, a decrease in sugar maple foliar concentrations of Ca ($P = 0.031$) and Mn ($P = 0.039$) was observed with increasing levels of added N. Compared to the control, foliar

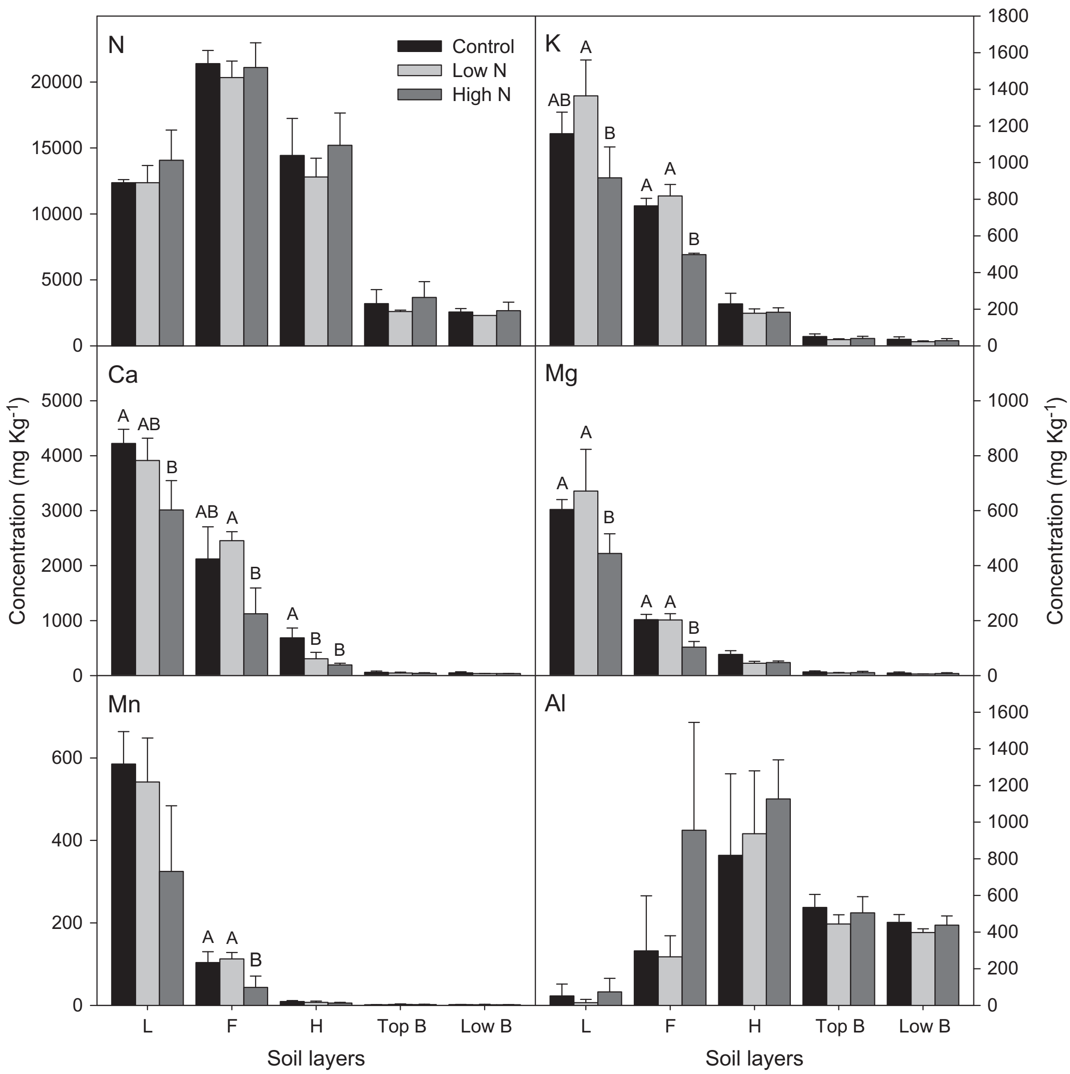

Fig. 1. Soil nutrient concentrations of soil layers at the LCW following 8 years of N additions (Control, Low N: threefold ambient deposition, High N: ten-fold ambient deposition).

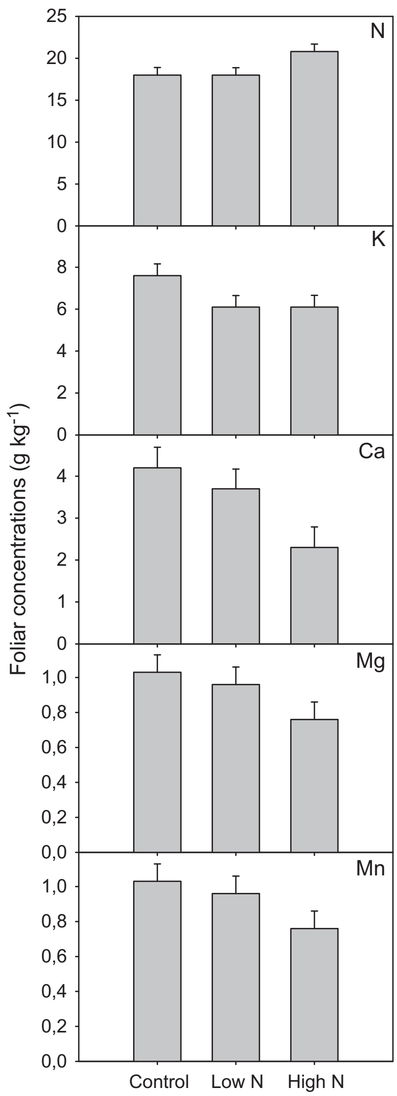

Fig. 2. Sugar maple foliar N, K, Ca, Mg and Mn concentrations at the LCW following 8 years of N additions (Control, Low N: threefold ambient deposition, High N: ten-fold ambient deposition).

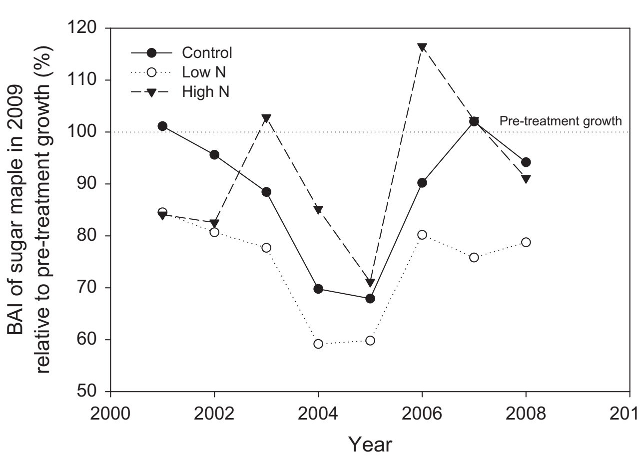

Fig. 3. Basal area increment of sugar maple at the LCW, relative to pre-treatment growth (1995–2000), following 8 years of N additions (Control, Low N: threefold ambient deposition, High N: ten-fold ambient deposition).

Ca decreased by 79% in the high N treatment, and foliar Mn decreased by 113%. By contrast, foliar N increased by 16% in the high N treatment, compared to the control ($P = 0.050$; Fig. 2). Foliar K and Mg also decreased in the high N treated plots (26% and 36%, respectively), but these differences were not significant ($P \geqslant 0.093$). No treatment effect was found for P ($P = 0.658$; data not shown).

Although the differences between treatments were not significant, crown dieback tended to increase in the high N treated plots. Mean rate of sugar maple dieback in the high N treated plots was 43% higher than in control plots (Control: 37 ± 9%; Low N: 39 ± 8%; High N: 52 ± 8%; $P = 0.221$). Also, sugar maple dieback in high N treated plots increased by 11% (± 4%) over the 2005 value, while the increases were smaller in the two other treatments (Control: 5 ± 4%; Low N: 4 ± 4%; $P = 0.144$). No treatment effect was observed for cumulative (2001–2009) and 2009 basal area growth (Fig. 3; $P \geqslant 0.0915$).

4. Discussion

4.1. Tree nutrition

In contrast with the short-term results of this experiment published by Moore and Houle (2009), where foliar N remained similar between treatments after 3 years of N additions, 8 years of chronic N additions caused a significant increase (+16%) in sugar maple foliar N concentrations in the high N treatment (Fig. 2). Other studies also reported similar results for sugar maple following repeated N applications (White et al., 1999; Zak et al., 2004; Elvir et al., 2010). These observations also agree with other fertilization studies in which foliar N concentration of control trees was below 2% (Hutchinson et al., 1998; Ellsworth, 1999; Zak et al., 2004; Elvir et al., 2006). The increase in the present study was observed despite the fact that N concentration and N mass remained similar between treatments in all soil layers. However, measures of total N concentration or of N mass may not be totally representative of potential changes in inorganic N availability.

The strong decrease in foliar Ca concentrations occurs in a context where sugar maple at the LCW site is already weakened by forest dieback, likely due to low soil cation availability (Moore et al., 2012). Foliar Ca concentration in control plots (Fig. 2) is among the lowest reported in the literature for sugar maple in northeastern North America, and is well below the foliar concentration threshold established for healthy sugar maples (e.g. Moore and Ouimet, 2010: ~6000 mg g^{-1}). In the high N treatment, foliar Ca concentration decreased to values as low as 2352 mg kg^{-1}, the lowest value ever reported for sugar maple (e.g. Moore and Ouimet, 2010). This is in accordance with the low base cation concentrations observed in the forest floor, particularly for the high N treatment (Fig. 1). The concentration of other base cations (K, Mg and Mn) in sugar maple foliage also decreased after N additions (Fig. 2). The strong decrease of Mn caused by the N additions (Fig. 2) contrasts with results of other studies, in which increases (Hutchinson et al., 1998) or no changes (Elvir et al., 2006) were reported following $(NH_4)_2SO_4$ addition. This suggests that an increase of N deposition in the future could further exacerbate Ca deficiency and disturb sugar maple nutrition for other base cations.

The decrease in foliar Ca concentration caused by relatively low rates of N addition at the LCW strongly contrasts with the results of Hutchinson et al. (1998) in Ontario, where Ca concentration remained unchanged in foliage (~10,000 mg kg^{-1}) after three years of massive N additions (up to 216 kg N ha^{-1} $year^{-1}$ as $(NH_4)_2SO_4$). These contrasting results could be explained by the different soil buffering capacities of these sites. Indeed, the Ontario stands had richer soils in terms of base cations, as compared to many maple

stands in eastern Canada that grow on soils developed from the granitic rock of the Canadian Shield (Duchesne et al., 2002). However, our results agree with studies at the Bear Brook Watershed in Maine, where medium- to long-term additions at a relatively low N rate (27 kg ha^{-1} $year^{-1}$ of $(NH_4)_2SO_4$) in base-poor soils had no effect on foliar Ca of sugar maple (Elvir et al., 2006; Elvir et al., 2010). Low foliar Ca concentrations observed for sugar maple at the LCW in untreated areas, and more obviously in the high N treated plots, can be explained by a decrease of exchangeable Ca in the forest floor (Houle et al., 1997). Moreover, studies have reported a decrease in mycorrhizal infection and microbial biomass in northern hardwood forests exposed to repeated N fertilization (Hutchinson et al., 1998; Van Diepen et al., 2010), which could have important effects on the nutrient cycling and uptake in these ecosystems.

Stand composition can also influence individual species responses to experimental N additions. Sugar maple composed approximately 80% of the stand basal area at our site and in Michigan (Pregitzer et al., 2008), but only 15% at the BBW in Maine (Elvir et al., 2003, 2010). Overall, too few studies report long-term results to allow making generalizations about the effects of stand composition (as well as soil conditions) on the response of sugar maple to N additions.

4.2. Crown dieback and basal area growth

Despite the significant decreases of Ca concentrations in foliage and in the forest floor due to the treatment, there were no statistically significant changes in sugar maple crown dieback or basal area growth (Fig. 3). Similar results for sugar maple growth were also reported, both after single (Leaf and Bickelhaupt, 1975; Stone, 1980; Ellis, 1979; Stanturf et al., 1989) and repeated N applications (Hutchinson et al., 1998; Elvir et al., 2003) in sugar maple stands. However, a significant increase in sugar maple woody biomass was reported in Michigan after 10 years of repeated N additions (Pregitzer et al., 2008).

The differences in dieback rate were not statistically significant between treatments at the LCW, but they reached 52% in the high N plots after 8 years, which is 43% more than the control and 11% more than the previous measurement in 2005. Although a strong decrease in foliar Ca was observed after treatments, a significant crown dieback and growth response could take longer to develop and would appear after a longer treatment duration. Another explanation could be that untreated sugar maple trees have already reached an unhealthy nutritional threshold (i.e. a value under 6000 mg kg^{-1}; Moore and Ouimet, 2010), which would explain why an additional nutritional stressor did not significantly affect vigor and growth of sugar maple. The same reason may explain the absence of a growth response after treatments, despite an increase in foliar N concentrations. The negative effect of decreased Ca concentration was probably more important than the potential positive effect of higher N concentrations.

4.3. Conclusion

The significant decreases of Ca in the forest floor and in the foliage of sugar maple at the LCW raise further concerns about the species' sustainability in weakly buffered forest soils. Although S emissions and deposition have been decreasing in recent decades, increasing atmospheric N deposition may lead to adverse effects similar to those that S deposition has had in the past on the soil base cation pool (Houle et al., 1997) and on sugar maple vigor (Duchesne et al., 2002). In this context, liming is presently the only known treatment that can mitigate the negative effects of acidic deposition on sugar maple nutrition in acidic, base-poor forest soils of eastern North America (Long et al., 2011; Moore et al., 2012).

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